

METHOD OF DECOMPOSING NITROGEN DIOXIDE

The present invention relates to a method of decomposing nitrogen dioxide (NO₂)
5 in a gas mixture to nitrogen monoxide (NO), for example an exhaust gas mixture of an
internal combustion engine.

Exhaust gases from internal combustion engines comprise a mixture of pollutants
including carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x)
10 and particulate matter (PM). The NO_x component can comprise nitrogen monoxide (NO) and nitrogen dioxide (NO₂). The level of these pollutants in exhaust gases from
internal combustion engines it is permissible to exhaust to atmosphere is regulated by
legislation. Such legislation can be met by engine design, engine management and/or
exhaust gas aftertreatment, and typically a combination of all three measures.

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A prior art exhaust system primarily for treating diesel exhaust comprises an
oxidation catalyst for oxidising NO in the exhaust gas to NO₂ and a downstream filter for
trapping PM. A process for treating diesel PM that uses this arrangement is described in
EP 0341382 or US patent no. 4,902,487, both of which are incorporated herein by
20 reference. The process comprises passing an exhaust gas, such as a diesel exhaust gas,
including PM and NO unfiltered over an oxidation catalyst to convert the NO to NO₂,
collecting PM on the filter and combusting the collected PM by reaction with the NO₂.
This technology is commercially available as Johnson Matthey's Continuously
Regenerating Trap or CRT®. Combustion of the PM in NO₂ results in CO and NO, with
25 a potential side-reaction leading to the complete reduction of the NO₂ to N₂ as described
in SAE 890404.

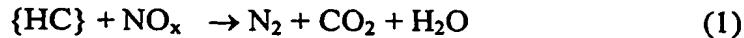
An advantage of this process is that it is possible to combust diesel PM at
temperatures of up to 400°C, whereas combustion of diesel PM in oxygen occurs at
30 about 500°C and above. This is significant since diesel exhaust gas is generally cooler
than exhaust gas from gasoline engines and PM would accumulate on the filter causing
back-pressure problems in the system if the process relied solely on combustion of PM in
oxygen without provision of additional means for increasing the exhaust gas
temperature; so-called "active" regeneration regimes.

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A problem with the process described in EP 0341382 is that, as exhaust emission legislation has tightened since the publication of that application, legislative bodies have begun to discuss limiting the amount of NO_x it is permissible to exhaust to atmosphere. For example, the California Air Resources Board (CARB) has proposed that a maximum 5 of 20% of tailpipe NO_x of the relevant drive cycle is emitted as NO₂ (See California's Diesel Risk Reduction Program, September 2000 and Title 13, California Code of Regulations, Chapter 14, section 2706.). NO₂ is toxic and can cause headaches, dizziness and nausea in low doses. It also has an objectionable smell. If there is insufficient PM on the filter to react with NO₂ generated over the oxidation catalyst or 10 the temperature of the exhaust gas is below a preferred range for combustion of PM in NO₂, NO₂ can slip past the filter and be undesirably exhausted to atmosphere.

This problem is particularly acute when internal combustion engines are used in confined spaces, such as mines, where vehicles are used to drill for, load, and transport 15 mined material to the surface. Many mining operations generate particulate matter, and so exhaust aftertreatment systems comprising filters for reducing the levels of PM emitted are being considered. Furthermore, explosives used to blast rock to recover a desired ore can generate NO₂. Accordingly, it would be an advantage to reduce the exhaust gas emissions of both PM and NO₂ to the atmosphere in closed environments to 20 improve the health and safety of miners. Indeed, the US Mine Safety and Health Administration prevents the use of diesel exhaust systems comprising diesel particulate filter systems that increase NO₂ emissions.

In selective catalytic reduction (SCR) by hydrocarbons (HC), HC react 25 selectively with NO_x, rather than with O₂, to form nitrogen, CO₂ and water according to equation (1):



30 The competitive, non-selective reaction with oxygen is given by Equation (2):



Two preferred groups of HC-SCR catalysts to selectively promote the desired reaction (1) for catalysing HC-SCR of NO_x (HC-SCR catalysts are also referred to as “lean NO_x catalysts” (LNC), “DeNO_x catalysts”, “NO_x occluding catalysts”, “NO_x reducing catalysts” and even “non-selective catalytic reduction catalysts” (because they can catalyse non-selective reactions e.g. Equation (2)). These two preferred groups are platinum on alumina and copper-substituted zeolite such as Cu/ZSM-5.

Pt-based catalysts tend to operate at relatively low temperature (peak activity ~250°C) and have a relatively narrow temperature window for HC-SCR activity whereas zeolite-based HC-SCR catalysts have a wider temperature window than Pt-based HC-SCR catalysts and operate at higher temperatures (peak activity ~400°C).

One potential solution to this problem is described in EP 0758713, where in one embodiment, an exhaust system comprises an optionally platinum-based oxidation catalyst and a diesel particulate filter (DPF) in the CRT® configuration and a NO_x absorbent downstream of the DPF. The NO_x absorbent can comprise platinum for oxidising NO to NO₂ in lambda > 1 exhaust gas compositions, rhodium for reducing NO_x to N₂ in lambda < 1 exhaust gas compositions and at least one substance selected from alkali metals such as potassium and caesium; alkali-earth metals such as barium and calcium; and rare-earth metals such as lanthanum for absorbing the NO₂ and storing it as the nitrate. Catalyst compositions comprising platinum, rhodium and a NO_x absorbent material are typically called NO_x traps.

In a second embodiment, a NO_x reducing catalyst is disposed downstream of the filter for catalysing the reduction of the NO_x to N₂ using diesel HC fuel and CO. The NO_x reducing catalyst can be a zeolite such as ZSM-5 ion exchanged with copper or iron, or mordenite supporting platinum. However, it is clear from EP 0758713 that HC reductant for reducing the NO_x is introduced into the exhaust system either by injecting additional fuel during the exhaust cycle or directly into the exhaust passage. In either case, injection is done always upstream of the CRT® oxidation catalyst.

In our WO 03/037507, we describe an exhaust system for an internal combustion engine comprising a catalyst, such as a platinum-based catalyst, for oxidising NO to NO₂ when the exhaust gas composition is $\lambda > 1$; and a filter disposed downstream of the NO oxidation catalyst, i.e. in the CRT® configuration. The filter can comprise an oxidation catalyst such as platinum and/or palladium, rhodium and a NO_x absorbent material, such as any of those described in EP 0758713 above. The filter component *per se* of this arrangement is described in Japanese patent no. 2722987.

We have investigated ways of catalytically decomposing NO₂ to NO and we have found that, very surprisingly, relatively acidic particulate refractory oxide materials are particularly active. In order to optimise conversion, we found that a relatively small amount of HC reductant is desirable. Without wishing to be bound by any theory, we believe that the HC forms a coke on the acidic materials and it is this that promotes the decomposition of NO₂ to NO. Certain metals can be included in the acidic materials to promote such coking, some of which metallised materials are known HC-SCR catalysts. Of course, the object of the HC-SCR is to convert all NO_x to N₂ and for this purpose C1 HC:NO_x ratios of from between 2 and 6 (see for example our WO98/40153) are preferred in the above-mentioned temperature windows. Whilst our results show that a relatively small amount of reduction to N₂ is effected, very good NO₂ conversion to NO can be achieved at much lower temperatures and C1 HC:NO_x ratios than for HC-SCR.

According to a first aspect, the invention provides a method of decomposing nitrogen dioxide (NO₂) to nitrogen monoxide (NO) in an exhaust gas of a lean-burn internal combustion engine, which method comprising adjusting the C1 hydrocarbon : nitrogen oxides (C1 HC:NO_x) ratio of the exhaust gas to from 0.1 to 2 and contacting this gas mixture with a particulate acidic refractory oxide selected from the group consisting of zeolites, tungsten-doped titania, silica-titania, zirconia-titania, gamma-alumina, amorphous silica-alumina and mixtures of any two or more thereof and passing the effluent gas to atmosphere.

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EP 0888816 discloses an exhaust emission control catalyst containing the three metals copper, praseodymium and yttrium, wherein the hydrocarbon: nitrogen oxide mole ratio is within a range of from 0.5 to 30.

EP 0541271 discloses a catalyst system for treating NO_x in the exhaust from a lean-burn gasoline-fueled engine, which system comprising a first stage catalyst containing a transition metal-exchanged zeolite (i.e. Cu-ZSM5), and a second stage catalyst, which is a three-way catalyst, for treating the effluent from the first stage catalyst. The engine is controlled such that the ratio of NO_x to HC in the exhaust gas is in the range of from 1/3 to 3/1 (i.e. minimum C₃H₆ of 250 ppm and NO_x of 200 – 400 ppm). Only the performance of the second stage catalyst and the first and second stage catalysts in combination is assessed in the Examples.

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In one embodiment, the particulate refractory oxide supports a metal or a compound thereof, which metal being selected from the group consisting of rhodium, palladium, iron, copper and mixtures of any two or more thereof.

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NO₂ can account for up to about 50% NO_x in the exhaust gas of an internal combustion engine. Therefore, according to one embodiment the HC:NO₂ ratio is adjusted to from 0.05 to 1.

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We have found that for the prescribed HC:NO_x ratios, NO₂ conversion is reduced at lower temperatures. In order to meet the proposed CARB threshold of a maximum of 20% NO₂ of NO_x emitted, in one embodiment we prefer that the step of adjusting the HC:NO_x ratio is performed only when the exhaust gas temperature is at 250°C and above. It will be noted that NO₂ conversion is possible at temperatures much below that required for HC-SCR for a similar catalyst i.e. above 250°C for NO₂ conversion vs. about 400°C for HC-SCR over Fe-Beta zeolite.

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According to a further embodiment, the step of adjusting the HC:NO_x ratio is done when the exhaust gas temperature is in a range that has been pre-determined to produce increased NO₂ in the exhaust system. Such temperature range will usually depend on the engine type and the duty of the vehicle. Illustrative embodiments include city centre buses comprising heavy duty diesel engines (250 - 300°C); buses in non-city centre locations (up to 400°C); and heavy duty diesel trucks (up to 500°C).

Potentially, the method according to the first aspect of the invention can be used to treat gas mixtures including NO₂ generated by any chemical, e.g. industrial, process. However, for the purposes of the present invention, the method is for treating an exhaust gas mixture derived from combustion of a hydrocarbon fuel, such as diesel fuel, gasoline fuel, natural gas (NG) or liquid petroleum gas (LPG) in an internal combustion engine.

According to a second aspect, the invention provides an exhaust system for an internal combustion engine, which system comprising a catalyst for decomposing nitrogen dioxide (NO₂) to nitrogen monoxide (NO) with a suitable reductant, and means, in use, for adjusting the C1 hydrocarbon : nitrogen oxides (C1 HC:NO_x) ratio in an exhaust gas upstream of the catalyst to from 0.01 to 2, which catalyst consisting of a particulate acidic refractory oxide selected from the group consisting of zeolites, tungsten-doped titania, silica-titania, zirconia-titania, gamma-alumina, amorphous silica-alumina and mixtures of any two or more thereof optionally supporting a metal or a compound thereof, which metal being selected from the group consisting of rhodium, palladium, iron, copper and mixtures of any two or more thereof.

In one embodiment, the means for adjusting is adapted to adjust the C1 HC:NO₂ ratio of the exhaust gas to from 0.05 to 1.

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According to a further embodiment, the adjustment means is controlled, in use, to operate when the exhaust gas temperature is above 250°C.

25 In another embodiment, the adjustment means is controlled, in use, to operate when the exhaust gas temperature is below 500°C.

Control of the adjustment means can be effected by suitable means comprising, in one embodiment, a processor which in turn can form part of the engine control unit (ECU) if desired.

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In order to control the C1 HC:NO_x ratio, it is desirable that the system comprises one or more sensors for inputting the status of one or more of the following conditions in the system: exhaust gas temperature; catalyst bed temperature; exhaust gas mass flow;

NO₂ in the exhaust gas, e.g. as detected by a suitable NO₂ sensor; manifold vacuum; ignition timing; engine speed; throttle position; lambda value of the exhaust gas composition; quantity of fuel injected in the engine; position of an exhaust gas circulation valve; and boost pressure.

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It will be understood that the C1 HC:NO_x ratio can be varied according to the or each input received. For example, at lower exhaust gas temperatures a higher ratio is desirable for a pre-determined NO₂ conversion, whereas a lower C1 HC:NO₂ ratio can be used at higher temperatures.

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According to another embodiment, the control means is operated according to stored look-up tables or an engine map in response to at least one of the above inputs.

15 Adjustment of the C1 HC:NO_x ratio to within the prescribed range can be done either by increasing the amount of HC or by adjusting the NO_x, e.g. by adjusting the amount of exhaust gas recirculation. Where HC in the system is to be increased, this can be done in a number of ways, such as by means for injecting the HC into the exhaust gas downstream of the engine; by means for adjusting the ignition timing of at least one engine cylinder; by means for adjusting fuel injection timing of at least one engine
20 cylinder; or, by means for adjusting the engine air-to-fuel ratio.

In one particular embodiment, the inputs are provided by air exhaust gas temperature sensor and a mass flow sensor. Since exhaust gas temperature correlates reasonably with the level of engine-out NO_x, and it is possible to model NO oxidation
25 over a catalyst in an exhaust system, such as the CRT®, an estimate of exhaust gas NO₂ can be derived. If the mass flow rate is also known it should be possible to calculate how much HC fuel e.g. diesel to inject to obtain the desired C1 HC:NO₂ ratio for NO₂ decomposition over the catalyst.

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In another embodiment, the NO₂ decomposition catalyst is disposed downstream of an oxidation catalyst comprising at least one PGM, preferably at least one of platinum and palladium. It is known from EP 0341382 or US patent no. 4,902,487 that such catalysts can oxidise NO in the exhaust gas to NO₂ at temperatures of up to 400°C (at

higher temperatures, the forward reaction is thermodynamically limited), and this is so even if the intended purpose of the catalyst is to catalyse some other reaction, e.g. the oxidation of diesel particulate matter, CO or a soluble organic fraction or volatile organic fraction of diesel hydrocarbons. However, importantly, where additional HC is
5 introduced into the exhaust system upstream of the NO₂ decomposition catalyst, this is done downstream of the oxidation catalyst. This is in clear contradistinction to the arrangement disclosed in EP 0758713 and we believe that the inventors in that case intended to inject the HC upstream of the oxidation catalyst in order to take advantage of any additional NO_x reduction that could be obtained over the PGM oxidation catalyst, or
10 to generate an exotherm over the catalyst for regenerating the diesel particulate filter. Naturally, if a NO₂ decomposition catalyst is disposed downstream of an oxidation catalyst and the oxidation catalyst is for generating NO₂ for combusting PM on a downstream filter, i.e. the CRT® system, the NO₂ decomposition catalyst is disposed downstream of the filter.

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According to a further embodiment, the oxidation catalyst is on a particulate filter, e.g. a diesel particulate filter or DPF. Such arrangement is sometimes called a "catalysed soot filter" or CSF. The catalyst can promote the combustion, i.e. reduce the combustion temperature, of soot and particulate matter on the filter. However, the
20 presence of an oxidation catalyst on the filter can also result in increased levels of NO₂ leaving the filter section of the filter relative to the amount of NO₂ entering the filter.

According to a further embodiment, the oxidation catalyst is associated with a NO_x absorbent material. One such arrangement is that the NO_x absorbent material,
25 typically at least one compound of an alkali metal e.g. potassium or caesium, at least one compound of an alkaline earth metal, such as barium, strontium or calcium, or at least one compound of a rare earth metal, for example lanthanum or yttrium, is associated with the oxidation catalyst. Generally, the compounds will be oxides but, in use, the compounds may also be present as hydroxides, carbonates or, following NO_x absorption
30 (as will be described hereinafter) nitrates.

In this arrangement, NO₂ generated over the oxidation catalyst during lambda > 1 conditions can be absorbed in the NO_x absorbent material and stored as the nitrate. Since

the NO_x absorbent material has a finite capacity to absorb NO_x, it is necessary periodically to regenerate it, i.e. to remove the stored NO_x. Generally, this is done in practice by transiently adjusting the lambda composition to lower the oxygen concentration of the exhaust gas, for example by introducing additional HC fuel into the
5 exhaust gas or by allowing less air into the combustion mixture. The resulting exhaust gas is "enriched" but need not result in a lambda <1 composition. The nitrate forms of the alkali, alkaline earth and rare earth metals are understood to be unstable in rich exhaust gas, and so NO_x is released, in what is believed to be a mixture of at least NO and NO₂.

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Typically, compositions comprising NO_x absorbent materials also comprise rhodium for reducing the NO_x to N₂ in the presence of the reductant. However, the rhodium NO₂ decomposition catalysts of the present invention do not include other PGM's such as platinum and /or palladium commonly used as oxidation catalysts. In
15 one arrangement, for example, the NO₂ decomposition catalyst is on a separate monolith downstream of the filter. In a particular embodiment, however, the NO₂ decomposition catalyst can be disposed on a downstream end of the filter.

The filter can be any suitable substrate including a wall-flow filter of ceramic
20 material such as silicon carbide or cordierite. Alternatively, it can be the device described in either EP 1057519 or WO 03/038248.

Examples of suitable zeolite components for the NO₂ decomposition catalysts are ZSM-5, β-zeolite, Y-zeolite or mordenite. Suitable silica to alumina molar ratios for
25 such zeolites are from 25 to 400, optionally 30 to 80.

The NO₂ decomposition catalysts supporting metals or compounds thereof can be prepared according to known methods such as wet impregnation of the at least one support material using a suitable metal salt followed by calcination, co-precipitation or
30 by ion exchange.

The silica-titania, zirconia-titania or tungsten-titania can be in the form of true mixed oxides or composite oxides. "Composite oxide" as defined herein means a largely

amorphous oxide material comprising oxides of at least two elements which are not true mixed oxides consisting of the at least two elements.

In one embodiment, the catalyst for use in the exhaust system according to the
5 invention contains from 0.1 to 5.0 wt% rhodium, such as from 0.25 to 2.5 wt% rhodium,
based on the total weight of the particulate refractory oxide.

In a specific embodiment, the catalyst consists essentially of 0.5 wt% rhodium on
gamma-alumina.

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In a further embodiment, the NO₂ decomposition catalyst contains from 1 to 10
wt% copper, such as from 2.5 to 7.5 wt% copper, based on the total weight of the
particulate refractory oxide. Where the particulate refractory oxide is a zeolite, it can be
impregnated, ion exchanged or co-precipitated onto the refractory oxide.

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In a specific embodiment the catalyst consists essentially of 5 wt% copper on
zeolite ZSM-5 and/or β-zeolite.

In a further embodiment, the catalyst contains from 1 to 10 wt% iron, such as
20 from 2.5 to 7.5 wt% iron, based on the total weight of the particulate refractory oxide.
Where the particulate refractory oxide is a zeolite, it can be impregnated, ion exchanged
or co-precipitated onto the refractory oxide.

In a specific embodiment the catalyst consists essentially of 5 wt% iron and the at
25 least one support is zeolite ZSM-5 and/or β-zeolite.

According to a further embodiment, the catalyst contains from 0.1 to 5.0 wt%
palladium, such as from 0.25 to 2.5 wt% palladium, based on the total weight of the
particulate refractory support.

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In a specific embodiment the catalyst consists essentially of 2 wt% palladium on
tungsten-titania.

According to a third aspect, the invention provides an internal combustion engine comprising an exhaust system according to the invention. Such engine can be fuelled by any suitable fuel such as diesel fuel, gasoline fuel, natural gas (NG) or liquid petroleum gas (LPG), but is preferably powered by diesel fuel.

According to a fourth aspect, the invention provides a vehicle, such as a mining vehicle, comprising an engine according to the third aspect of the invention.

It is believed that the NO₂ decomposition catalysts described herein, in addition to catalysing the reduction of NO₂, may also catalyse the reduction of SO₃ to SO₂ in exhaust gas conditions and can be used where such reaction is desirable, e.g. to reduce the amount of SO₃-derived particulate observed in diesel drive cycles.

In order that the invention may be more fully understood, the following Examples are provided by way of illustration only and with reference to the accompanying drawings, in which:

Figure 1 is a graph showing %NO₂ conversion as a function of temperature (°C) for NO₂ decomposition catalysts with and without diesel fuel injection (about 120ppm C1 (MK1)) relative to a blank reactor control;

Figure 2 is a graph showing NO production from NO₂ in the presence of diesel fuel as a function of temperature relative to a blank reactor control;

Figure 3 is a graph showing NO₂ decomposition over a Cu/Beta-30 zeolite catalyst at HC:NO₂ of 0.5 as a function of temperature;

Figure 4 is a graph showing %NO₂ conversion over a Cu/Beta-30 zeolite catalyst at HC:NO₂ of 0.5 as a function of temperature;

Figure 5 is a graph showing NO₂ / NO_x ratio (%) over a Cu/Beta-30 zeolite catalyst at HC:NO₂ of 0.5 as a function of temperature;

Figure 6 is a graph showing NO₂ decomposition over a Cu/Beta-30 zeolite catalyst at HC:NO₂ of 0.25 as a function of temperature;

5 Figure 7 is a graph showing NO₂ / NO_x ratio (%) over a Cu/Beta-30 zeolite catalyst at HC:NO₂ of 0.25 as a function of temperature;

Figure 8 is a graph showing NO₂ /NO_x ratio (%) over a Cu/Beta-30 zeolite catalyst at HC:NO₂ of 0.25 as a function of temperature;

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Figure 9 is a graph showing %NO₂ decomposition as a function of temperature comparing the activity of aged 5Cu/Beta-30 zeolite catalysts;

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Figure 10 is a graph showing %NO₂ decomposition as a function of temperature comparing the activity of a series of 5Cu/zeolite catalysts;

Figure 11 is a graph showing %NO₂ decomposition as a function of temperature comparing the activity of two 5Cu/ZSM5 catalysts having zeolites of differing silica to alumina molar ratios;

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Figure 12 is a graph showing %NO₂ decomposition as a function of temperature comparing the activity of coked and uncoked 5Cu/Beta-30 catalysts;

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Figure 13 shows a temperature programmed oxidation (TPO) trace of a "coked" 5Cu/Beta-25 zeolite catalyst;

Figure 14 shows a graph of %NO₂ as a function of temperature comparing the activity of a series of non-zeolite catalysts compared to 5Cu/ZSM5-30; and

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Figure 15 shows a graph of %NO₂ decomposition activity for a series of copper-containing non-zeolite catalysts compared to 5Cu/Beta-25.

Example 1

A series of catalysts were analysed on a simulated catalyst activity test (SCAT) gas rig for their abilities to decompose NO₂ in a simulated exhaust gas reaction mixture
5 containing 200ppm NO₂, about 120ppm C1 diesel fuel (MK1), 12% O₂, 4.5% CO₂, 4.5% H₂O and 20ppm SO₂, N₂ balance (C1 HC/NO₂ ≈ 0.6). Each catalyst was heated in a 10°C-a-minute ramp in the reaction mixture from 150°C to 500°C. The catalysts tested
10 were 5 wt% copper ion exchanged ZSM5-30 zeolite ((by total weight of the support) 5Cu/ZSM5-30), 0.5 wt% rhodium on gamma-alumina ((by total weight of the particulate support) 0.5Rh/Al₂O₃) and 5 wt% copper ion exchanged β-zeolite-30 ((by total weight of the support) 5Cu/Beta-30).

As a control, NO₂ decomposition over the blank reactor with mesh was measured and the 5Cu/β-zeolite-30 catalyst was tested with the above mixture but in the absence of
15 diesel fuel. As a further test, the 5 wt% copper ion exchanged ZSM5-30 zeolite was tested in the above exhaust gas reaction mixture wherein the 200ppm NO₂ was exchanged for 100ppm NO and 100ppm NO₂, i.e. 1:1 NO:NO₂. The results of NO₂ decomposition and NO production from NO₂ are set out in Figures 1 and 2.

20 It can be seen that the addition of diesel fuel improves the low temperature conversion of NO₂ to NO. The 5Cu/β-zeolite-30 catalyst is the most active catalyst giving 100% NO₂ removal from about 200 to about 350°C.

25 Changing the gaseous NO_x composition from 200ppm NO₂ to 100ppm NO/100ppm NO₂ has no perceptible effect on the low temperature performance, although the activity does fall off more sharply at higher temperatures when using the NO/NO₂ mix. Whether this is due to NO inhibition (perhaps unlikely at this high temperature) or is a kinetic/reaction order effect associated with reducing the inlet NO₂ concentration from 200 to 100ppm is not yet clear.

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The mass balances for NO₂ decomposition vs. NO production at temperatures in the 300–400°C range do not correlate. For example, at 350°C the NO₂ removal is 100%, but only around 150ppm NO is seen in the gas phase (instead of the 200ppm which we

would expect to see if all of the NO₂ was being decomposed to NO). We believe, therefore, that we are getting some lean NO_x reduction here, using stored HC and gas phase HC to remove the NO_x - the temperature window fits with this hypothesis.

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Example 2

In a laboratory, a bench mounted, heavy-duty diesel engine fitted with a CRT® exhaust gas after-treatment system as described in EP 0341832, i.e. a platinum on aluminium-based oxidation catalyst for oxidising NO to NO₂ and a downstream ceramic wall-flow diesel particulate filter, was used to test the principle of NO₂ decomposition shown in Example 1 in "real-world" conditions. A diesel fuel injector was disposed downstream of the filter and a ceramic monolith of 400 cells per square inch (62 cells cm⁻²) was coated with a 5Cu / Beta-zeolite-30 catalyst of Example 1.

15 NO and NO₂ sensors were used to detect the amounts of these gases at various points in the exhaust system, and the amounts of detected NO₂ were used to calculate an amount of diesel fuel to be injected to obtain a C1 HC: NO₂ ratio of 0.5 and 0.25 over the catalyst. (Since approximately 50% of NO_x downstream of the CRT® oxidation catalyst at up to about 400°C is NO₂, these values correlate to a C1 HC: NO_x ratio of 20 approximately 1.0 and 0.5 respectively). The engine load was adjusted to increase temperature in the exhaust system and measurements were made after the system had been run at steady state conditions.

25 Figures 3 – 5 show the results for C1 HC: NO₂ of 0.5. In the legends, the NO₂ decomposition catalyst is referred to as a "clean-up" catalyst. It can be seen that good NO₂ decomposition activity is observed, although the % NO₂ decomposition does fall off at temperatures below about 300°C. A small amount of NO_x conversion of 7% peak at about 325°C is observed (results not shown). Under the conditions used, NO₂/NO_x is below 20% at every temperature except the lowest (250°C). The fall off in NO₂/NO_x 30 ratio after the CRT® oxidation catalyst is due to the thermodynamic equilibrium favouring NO over NO₂. Negligible HC slip was observed (results not shown).

At C1 HC:NO₂ of 0.25 (results shown in Figures 6 – 8), good NO₂ decomposition is still observed, but the conversion peaks at 80%. Again, a small amount of NO_x conversion (peak 6% at 325°C) was seen. Under the conditions used, NO₂/NO_x is below 20% at temperatures above 325°C. Negligible HC slip was observed.

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Example 3

In order to investigate the effects of catalyst ageing, a 5Cu/Beta-30 catalyst was aged in air at 500°C, at 400°C in a gas mixture of air, 10% H₂O and 50 ppm SO₂ for 10 63 hours (lean hydrothermal sulphur ageing or LHSA), and at 600°C for 162 hours in a gas mixture of air and 10% H₂O (lean hydrothermal ageing or LHA). The catalysts were tested on a SCAT gas rig for their abilities to decompose NO₂ in a simulated gas reaction mixture containing 200 ppm NO₂, 100 ppm C1 diesel fuel (MK1), 12% O₂, 4.5% H₂O, 4.5%CO₂, 20 ppm SO₂ and N₂ balance in the manner otherwise explained in 15 Example 1. The results are shown in Figure 9.

It can be seen that lean hydrothermal ageing actually improves the %NO₂ decomposition activity at lower temperatures. Significantly, lean hydrothermal sulphur ageing increases the low temperature catalyst activity even more. Since LHSA would be 20 expected to sulphate the catalyst components, this observation suggested that the mechanism for catalyst activity involves coking of the catalyst, because sulphation would increase the acidity of the catalyst. Increased activity can increase coking on the catalyst derived from hydrocarbon contacting it. A further series of experiments were organised in order to test this theory.

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Example 4

One way of increasing acidity of a zeolite catalyst is to alter the silica to alumina molar ratio of the material. To investigate the theory that catalyst NO₂ decomposition 30 activity is linked to catalyst acidity, a series of zeolite-catalysts were tested having different silica to alumina molar ratios. Specifically 5 Cu/ZSM-30 (i.e. a ZSMS zeolite with a silica to alumina molar ratio of 30), 5 Cu/ZSM-300, 5 Cu/Beta-30, 5 Cu/Beta-300 and non-metallised Beta-300 were prepared and tested on a SCAT gas rig according to

the procedures set out in Example 1 in a gas mixture according to Example 3. The results are shown in Figures 10 and 11.

It can be seen that the lower silica to alumina molar ratio zeolites, i.e. the more 5 acidic materials, are more active. Also, that non-metallised zeolite is active for NO₂ decomposition, but the metallised catalysts are more active. This suggests that the metal has a role in coking. Increasing the silica to alumina molar ratio in β-zeolites does not affect low temperature NO₂ decomposition performance as much as ZSM-5.

10 A further investigation to show that catalyst coking is involved with NO₂ decomposition activity was undertaken. In this experiment, a 5 Cu/Beta catalyst was exposed to a gas mixture intended to induce coking for 10 hours at 300°C. This mixture consisted of 2000 ppm C1 MK1 diesel fuel, 12% O₂, 4.5% H₂O, 4.5% CO₂, 20 ppm SO₂, balance N₂. The catalyst was tested in a SCAT gas rig using the procedure set out in 15 Example 1 and the gas mixture at Example 3. The results are shown in Figure 12.

The “coked” sample was tested, then cooled and the same sample was re-tested, hence “ramp 1” and “ramp 2”. If coke is involved in the NO₂ decomposition reaction, it would be expected that ramp 2 would show less activity than ramp 1 as some coke would 20 be used up in ramp 1, and this was confirmed by the experiment, with the difference in low temperature activity. At higher temperatures, coke may be being replenished by reaction of C1 hydrocarbon in the feed gas on the catalyst.

A further confirmation of coke formation on the catalysts is shown by 25 temperature programmed oxidation (TPO) analysis of a coked 5 Cu/β-zeolite-25 sample (coking by exposure to 11% O₂, C1 ~ 700 ppm (MK1 diesel fuel) at 300°C for 16 hours). TPO analysis was performed on a temperature programmed desorption rig in 5% O₂, balance He at a ramp rate of 10°C min⁻¹. Evolution of CO₂ was monitored by mass spectrometer. The results are shown in Figure 13.

Example 5

The following non-zeolite catalysts were prepared: 0.5wt% rhodium on gamma-alumina (0.5Rh/A₂O₃), 2 wt% palladium on tungsten-titania (2Pd/WO₃ – TiO₂), tungsten-titania *per se*, 10wt% copper on gamma alumina (10 Cu/A₂O₃) and 5 wt% copper on tungsten-titania (5 Cu/WO₃ – TiO₂). The catalysts were tested in the matter set out in Example 1 using the gas mixture described in Example 3. The results of %NO₂ decomposition as a function of temperature are shown on Figures 14 and 15, compared with 5 Cu/zeolite catalysts.